

RELATIVISTIC SIGNATURES AT THE GALACTIC CENTRE

E. M. Howard

*Faculty of Science and Engineering,
Department of Physics and Astronomy,
Macquarie University,
Sydney, NSW, Australia
* E-mail: katie.howard@mq.edu.au
www.mq.edu.au*

The current studies of the inner few parsecs at the Galactic Centre provide enough indications of a supermassive black hole, object associated with an unusual, variable (radio, near-infrared, and X-ray) source Sgr A*. The highly compact nature of the distributed mass as well as the intense gravitational field suggest the indisputable presence of dark matter.

There is also evidence that the main emissions from Sgr A* originate from the accretion disc from within ten gravitational radii from the dynamical centre. In order to understand the physics behind the observed time-dependent physical phenomena, we study light curves and spectra of emissions originated at the surface of the accretion disk, close to the event horizon, near the marginally stable orbit of a Kerr (rotating) black hole.

Our main goal is the investigation and deep analysis of the physical processes responsible for the variable observed emissions from the compact radio source Sgr A*.

Keywords: Sgr A*, light curve, hot spot, black hole physics, Galactic Center, accretion disc, relativity effects

1. Introduction

Due to its relative proximity, SgrA* provides favorable circumstances to a better understanding of the processes responsible for the observed time-dependent phenomena.

Apparently, the emissions from Sgr A* are originated in radiative processes in keplerian motion, with a peak occuring within several Schwarzschild radii ($r_S \equiv 2GM/c^2$) of the centre.

Latest theoretical models are trying to address the question of what the spectral line profiles or continuum may tell us about the black hole

properties, and analyze the constraining parameters and characteristics of the accretion disc close to the event horizon. We take into account emissions from within the last stable orbit of a rotating (Kerr) black hole or from the region near above the marginally stable orbit

Using fully relativistic ray-tracing methods, we analyze the constraining parameters and principal characteristics of the black hole and study the main imprints of both special and general relativistic effects on the time-resolved emission phenomena.

We consider all relativistic effects (energy shift, aberration, light bending, lensing and relative time delay) near a Kerr black hole. General and special relativistic effects play a crucial role in the time-dependent behaviour, particularly for a maximally rotating Kerr black hole.

By integrating the photon geodesic paths between a position inside a spot located within the accretion disk and an observer positioned at infinity, we obtain time dependent spectra for an orbiting or infalling spot co-moving with the accretion disk, in a deep gravitational potential.

A detailed time-resolved analysis makes possible the study of the evolution of the emitting region, close to the event horizon as well as the diagnosis of the light curves of the variable emission region, for various spectral emissivity profiles, different viewing directions of the distant observer and different locations of the spot relatively to the local observer, the event horizon and the center of the disk.

2. Basic assumptions and objectives

We consider a complete system comprising a black hole, an accretion disc and a co-rotating spot within the cold accretion disk.

The gravitational field is described in terms of Kerr metric, for a rotating black hole and particularly for a non-rotating black hole. Therefore, both static Schwarzschild and rotating Kerr black hole cases are considered.

The co-rotating Keplerian accretion disc is geometrically thin and optically thick, therefore we take into account only photons coming from the equatorial plane directly to the observer. The spot is orbiting within the disk near the rotating black hole.

We also assume that the matter in the accretion disc is cold and neutral.

A fully relativistic ray tracing code is used to analyze how the considered effects affect and modify the Sgr A* disk emissions originated in a co-moving (local) frame with the accretion disk, up to a distant observer, located at infinity. The observer is placed in the azimuthal direction $\varphi = \pi/2$.

Relativistic effects alter the shape of the spectra, more significantly at

large inclination angles and play an important role in the time-dependent emission processes, especially in the case of a maximally rotating Kerr black hole.

3. Summary

We try to address various questions concerning the validity of the simple spot model and the role of the relativistic effects in the observed phenomena. We calculate time-dependent spectra of both cases of an orbiting or a free-falling spot.

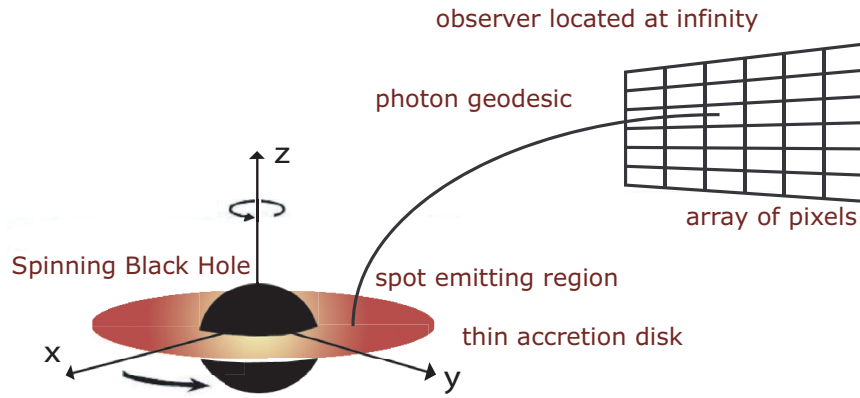


Fig. 1. Ray tracing in Kerr geometry

The code integrates the local emission in polar coordinates on the disc and, as a consequence, we may handle emission originated in a non-axisymmetric area of integration.

In the axisymmetric case, the local emission is integrated in one dimension, the radial coordinate of the disc.

We are able to:

- 1) gather information about the black-hole spin
- 2) study free-falling photons from the marginally stable orbit down towards the black hole horizon. This provides us with information about the plunge region, the area between the Event Horizon and the last stable orbit

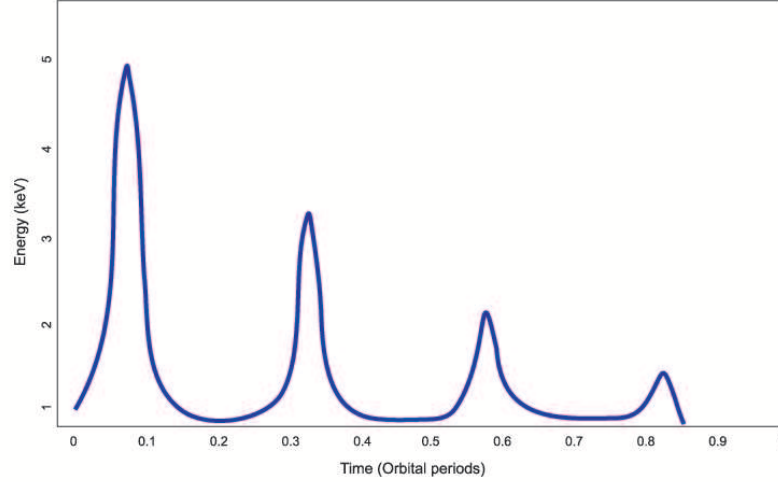


Fig. 2. Spectrum of an in-falling spot near to the horizon of an extreme Kerr black hole, with spin parameter $a=0.998$. Energy is on the ordinate, time on the abscissa.

3) work with the emissivity as dependent on both of the polar coordinates within the equatorial plane

4) deal with time variable spectra, therefore handle non-stationary cases, making possible the study of the time evolution of the emitting region.

5) study light curves for different inclination angles of the observer relative to the disk axis (θ_o) and analyze the dependence of the variability on the inclination.

6) choose a non-axisymmetric emission area, therefore control the size and shape of the spot

7) consider non-axisymmetric geometry of accretion flows

8) analyze the general and special relativity effects that influence photons paths along null geodesics towards an observer located at infinity

9) as the photon paths are integrated in Kerr ingoing coordinates, this allows us to study the Kerr geometry and test the metric

Emission starts within a localized spot on the accretion disc. We consider two cases, whether the spot moves with a Keplerian velocity along a stable circular orbit or, if close to the marginally stable orbit, it plunges into the black hole.

The intrinsic intensity at each point depends on the energy shift of the

photons and it is time dependent.

Photons emerging from the spot area would be affected by all relativistic imprints. The KYSPOT code by Dovciak et al. takes all special and general relativistic effects into account by using pre-calculated sets of transfer functions that map various properties of the emission region in the accretion disk onto the sky plane (Cunningham 1975, 1976).

The transfer function, obtained by integration of the geodesic equation, correlates the flux in the local frame comoving with the disk, to the flux as seen by an observer located at infinity.

Spectral line profiles are obviously affected by relativistic smearing but due to the power-law character of the relativistic imprints, the main shape of the primary continuum profile remains intact.

Only the central gravity potential influences the trajectories of the photons towards the observer.

The functions are calculated for different values of observer inclination angle and black hole horizons.

The binary extensions contain information for different radii and different values of g -factor, defined as the ratio between the photon energy observed at infinity and the local photon energy as emitted from the disc.

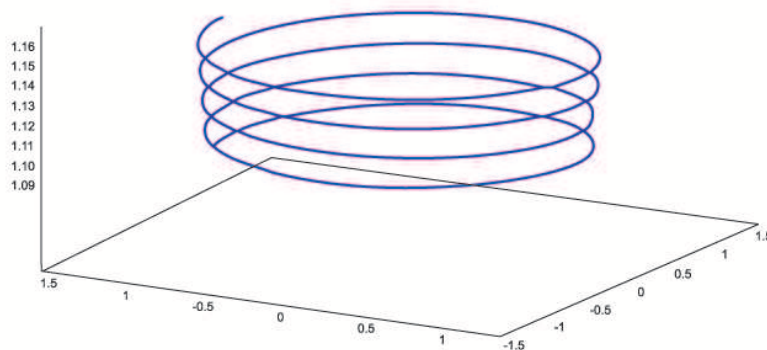


Fig. 3. Plunging trajectory of a photon into the event horizon of an extreme Black Hole

We obtain time-dependent spectra for various viewing directions of a distant observer based on different emissivity profiles and various angular momenta of the black hole.

The relativistic corrections on the local emission are parameterized by

the black hole spin and the observer's inclination angle.

The intrinsic emissivity is specified in the frame co-moving with the disc medium and it is defined as a function of r , φ and t in the equatorial plane. When the geodesic integration is ended, after the transfer of photons to the distant observer is performed, Boyer-Lindquist coordinates will replace the initial Kerr ingoing coordinate system.

The observed spectra depend on the position of the spot with respect to the disk normal. We obtain light curves of the variable emission region, for different position and angles (azimuthal and polar) of the spot relatively to the distant observer, the event horizon and the center of the disk. We also consider different spin parameter values, various viewing angles and different sizes of the emitting spot.

4. References and literature

References

1. Arnaud K. A., 1996. XSPEC: The first ten years. In *Astronomical Data Analysis Software and Systems V*, eds. Jacoby G. & Barnes J., ASP Conf. Series, vol. 101, p. 17
2. Beckwith K., & Done C., 2004. Iron line profiles in strong gravity. *MNRAS*, in press (astro-ph/0402199)
3. Carter B., 1968. Global structure of the Kerr family of gravitational fields. *Phys. Rev.*, 174, 1559
4. Chandrasekhar S. 1960. *Radiative Transfer*. Dover publications, New York
5. Chandrasekhar S., 1992. *The Mathematical Theory of Black Holes*. New York, Oxford University Press
6. Connors P. A., & Stark R. F., 1977. Observable gravitational effects on polarized radiation coming from near a black hole. *Nature*, 269, 128
7. Connors P. A., Piran T., & Stark R. F., 1980. Polarization features of X-ray radiation emitted near black holes. *ApJ*, 235, 224
8. Dovčiak M., 2004. PhD Thesis (Charles University, Prague)
9. Dovčiak M., Karas V., & Yaqoob T., 2004. An extended scheme for fitting X-ray data with accretion disc spectra in the strong gravity regime. *ApJS*, 153, 205
10. Fabian A. C., Iwasawa K., Reynolds C. S., & Young A. J., 2000. Broad iron lines in active galactic nuclei. *PASP*, 112, 1145
11. Fanton C., Calvani M., de Felice F., & Čadež A., 1997. Detecting accretion discs in active galactic nuclei. *PASJ*, 49, 159
12. George I. M., & Fabian A. C., 1991. X-ray reflection from cold matter in active galactic nuclei and X-ray binaries. *MNRAS*, 249, 352
13. Ghisellini G., Haardt F., & Matt G., 1994. The contribution of the obscuring torus to the X-ray spectrum of Seyfert galaxies – a test for the unification model. *MNRAS*, 267, 743
14. Gierliński M., Maciolek-Niedźwiecki A., & Ebisawa K., 2001. Application of a relativistic accretion disc model to X-ray spectra of LMC X-1 and GRO J1655-40. *MNRAS*, 325, 1253
15. Haardt F. 1993. Anisotropic Comptonization in thermal plasmas – Spectral distribution in plane-parallel geometry. *ApJ*, 413, 680

16. Kato S., Fukue J., & Mineshige S., 1998. *Black-Hole Accretion Discs*. Kyoto, Kyoto Univ. Press
17. Krolik J. H., 1999. *Active Galactic Nuclei*. Princeton University Press, Princeton
18. Laor A., Netzer H., & Piran, T., 1990. Massive thin accretion discs. II – Polarization. *MNRAS*, 242, 560
19. Laor A. 1991. Line profiles from a disc around a rotating black hole. *ApJ*, 376, 90
20. Martocchia A., Karas V., & Matt G., 2000. Effects of Kerr space-time on spectral features from X-ray illuminated accretion discs. *MNRAS*, 312, 817
21. Matt G., Perola G. C., & Piro L., 1991. The iron line and high energy bump as X-ray signatures of cold matter in Seyfert 1 galaxies. *A&A*, 247, 25
22. Matt G., Perola G. C., Piro L., & Stella L., 1992. Iron K-alpha line from X-ray illuminated relativistic discs. *A&A*, 257, 63; *ibid.* 1992, 263, 453
23. Misner C. W., Thorne K. S., & Wheeler J. A., 1973. *Gravitation*. San Fransisco, W.H.Freedman & Co.
24. Novikov I. D., & Thorne K. S., 1973. In *Black Holes*, eds. DeWitt C., DeWitt B. S. New York, Gordon & Breach, p. 343
25. Phillips K. C., & Mészáros P., 1986. Polarization and beaming of accretion disc radiation. *ApJ*, 310, 284
26. Rauch K. P., & Blandford R. D., 1994. Optical caustics in a Kerr space-time and the origin of rapid X-ray variability in active galactic nuclei. *ApJ*, 421, 46
27. Reynolds C. S., & Nowak M. A., 2003. Fluorescent iron lines as a probe of astrophysical black hole systems. *Phys. Rep.*, 377, 389
28. Schnittman J. D., & Bertschinger E., 2004. The harmonic structure of high-frequency quasi-periodic oscillations in accreting black holes. *ApJ*, 606, 1098
29. Walker M., & Penrose R., 1970. On quadratic first integrals of the geodesic equations for type {22} spacetimes. *Commun. Math. Phys.*, 18, 265